National Aeronautics and Space Administration

Multi-objective hybrid optimal control for Multiple-flyby interplanetary mission design using Chemical propulsion

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code 595

NAVIGATION & MISSION DESIGN BRANCH

NASA GSFC

Introduction to the General Interplanetary Mission Design Problem

- The interplanetary design problem is composed of both discrete and real-valued decision parameters:
  - Choice of destination(s), number of planetary flybys, identities of flyby planets
  - Launch date, flight time(s), epochs of maneuvers, maneuver magnitudes and directions, flyby altitudes, etc.
- For example, for a near-Earth asteroid mission, the designer must choose:
  - The optimal asteroid from a set of scientifically interesting bodies provided by the customer
  - Whether or not to perform planetary flybys on the way to the main belt and, if so, at which planets
  - Optimal trajectory from the Earth to the chosen asteroid by way of the chosen flyby planets

Automated Mission Design via Hybrid Optimal Control

- Break the mission design problem into two stages, or “loops”
  - “outer-loop” picks sets of destinations, planetary flybys, sizes the power system, can pick propulsion system – a <u>discrete</u> optimization problem
  - “inner-loop” finds the optimal trajectory for a given candidate outer-loop solution – a <u>real-valued</u> optimization problem
  - For the outer-loop to work, the inner-loop must function autonomously (i.e. no human interaction)

Multi-Objective Hybrid Optimal Control

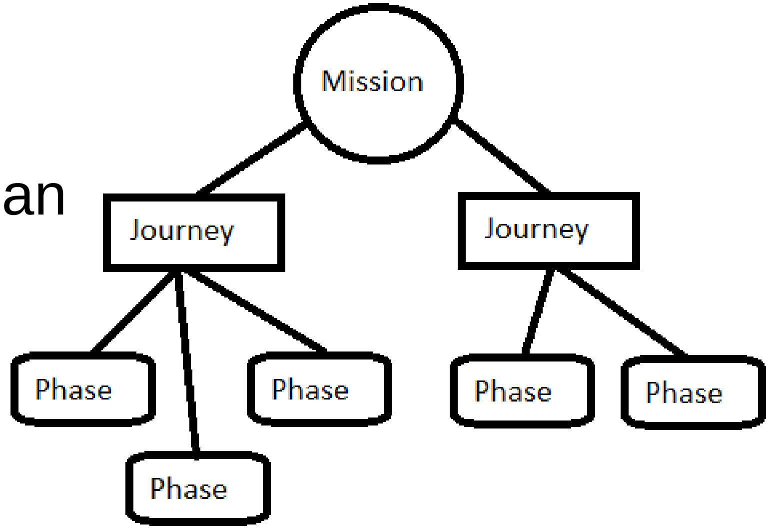
- The customer (scientist or project manager) most often does not want just one point solution to the mission design problem
- Instead, an exploration of a multi-objective trade space is required
- For a typical main-belt asteroid mission the customer might wish to see the trade-space of:
  - Launch date vs
  - Flight time vs
  - Deliverable mass
  - While varying the destination asteroid, planetary flybys, launch year, etc.
- To address this question we use a multi-objective discrete outer-loop which defines many single objective real-valued inner-loop problems

Outer-Loop Transcription and Optimization

- The outer-loop finds the non-dominated trade surface between any set of objective functions chosen by the user
- Non-dominated surface means “no point on the surface is superior to any other point on the surface in all of the objective functions”
- The outer-loop solver may choose from a menu of options for each decision variable
- The choices made by the outer-loop solver are used to define trajectory optimization problems to be solved by the inner-loop

Anatomy of a Mission

- Break mission into a set of “journeys,” each of which in turn is broken into “phases”
- The endpoints of a journey are chosen in the problem assumptions
- The endpoints of a phase (i.e. a flyby target) may be chosen by the user or an Outer-Loop solver



Outer-Loop Transcription: An Example

Launch Year

Code	Year
0	2020
1	2021
2	2022
3	2023
4	2024
6	2025
7	2026
8	2027
9	2028
10	2029

Flight Time Upper Bound

Code	# Years
0	5
1	6
2	7
3	8
4	9
5	10
7	11
8	12

First Asteroid

Code	Body
0	Ceres
1	Pallas
2	Juno
3	Vesta
4	Astraea
5	Hebe
6	Iris
7	Flora
…	(475 choices)

Second Asteroid

Code	Body
0	Ceres
1	Pallas
2	Juno
3	Vesta
4	Astraea
5	Hebe
6	Iris
7	Flora
…	(475 choices)

First Journey First Flyby

Code	Body
0	Earth
1	Mars
2	Jupiter
3	No flyby
4	No flyby
5	No flyby

First Journey Second Flyby

Code	Body
0	Earth
1	Mars
2	Jupiter
3	No flyby
4	No flyby
5	No flyby

Second Journey Flyby

Code	Body
0	Earth
1	Mars
2	Jupiter
3	No flyby
4	No flyby
5	No flyby

Sample Mission

	Flight Time Upper Bound	Asteroid 1	Potential Planetary Flyby 1	Asteroid 2	Potential Planetary Flyby 2
Code	4	0	1	1	1
Translation	8 y	Ceres	Mars	Pallas	none

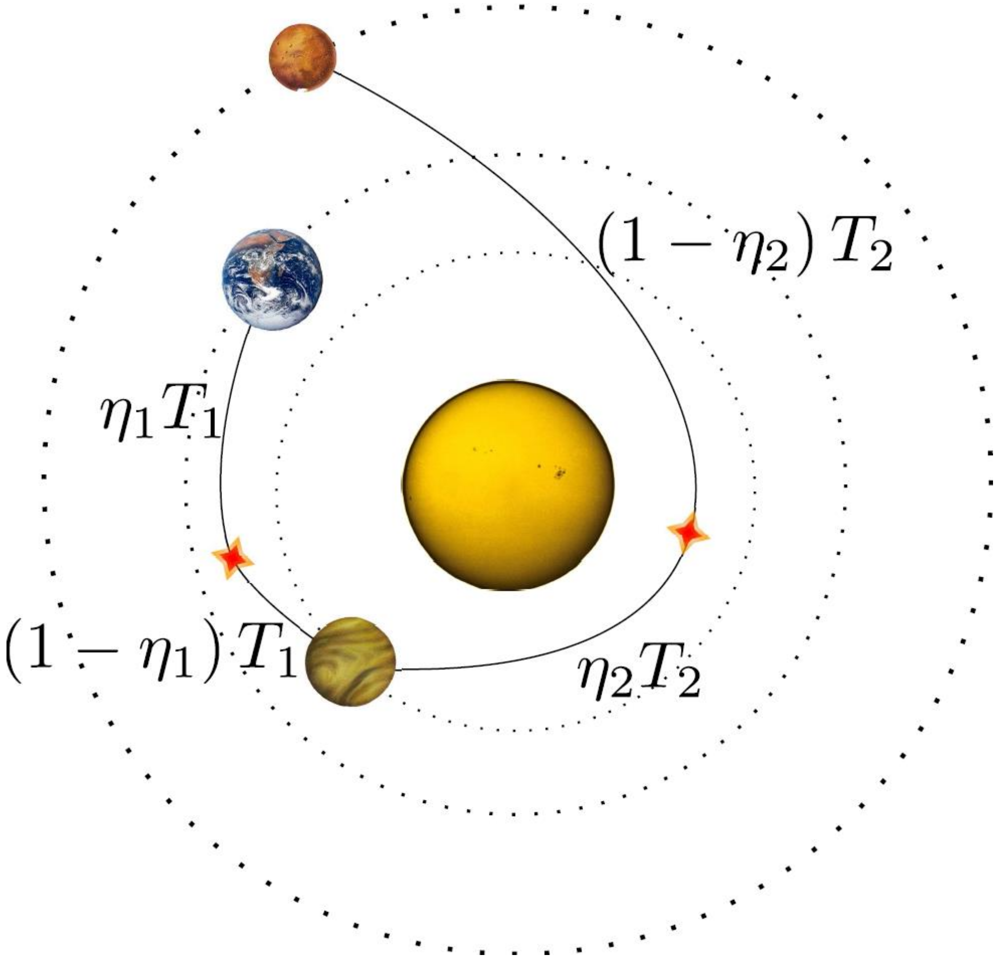
Multi-Objective Optimization via NSGA-II

- The outer-loop optimization problem is solved using a discrete multi-objective solver, in this case Non-Dominated Sorting Genetic Algorithm II (NSGA-II)
- NSGA-II finds the non-dominated front, surface, or hyper-surface between any number of objectives chosen by the user

Inner-Loop Modeling and Optimization

- The inner-loop solves a real-valued trajectory optimization problem which is defined by each candidate solution to the outer-loop problem
- The inner-loop must function autonomously because the problems are generated in real time and there is no opportunity for human intervention
- The outer-loop is only as good as the solutions to the inner-loop problem, so the inner-loop must be robust
- A given run of the outer-loop may require hundreds or even thousands of runs of the inner-loop, so the inner-loop must be fast
- If the individual inner-loop runs are independent then many of them can be run in parallel

Multiple Gravity Assist with 1 Deep-Space Maneuver (MGADSM)



Inner-Loop Objective Function – Maximize Delivered Mass

- Traditionally the objective function for a chemical mission is to minimize total Δv because it is linear
- Δv is used as an analog for mass via the exponential form of Tsiolkovsky's rocket equation

$$m_f = m_0 \mathrm{e}^{-\Delta v/c} \quad (1)$$

- However m_0 is actually a function of hyperbolic excess velocity C_3, so just optimizing Δv does not optimize spacecraft mass
- On the other hand, the derivative of (1) with respect to Δv is very steep and therefore (1) is difficult for a gradient-based optimizer to handle. Instead we find a transformation of (1) works well:

$$J = log10\left(m_f\right) = log10(m_0 \mathrm{e}^{-\Delta v/c}) \quad (2)$$

- Launch vehicles are modeled using a polynomial fit

$$m_0 = \left(1 - \sigma_{LV}\right)\left(a_{LV}C_3^5 + b_{LV}C_3^4 + c_{LV}C_3^3 + d_{LV}C_3^2 + e_{LV}C3 + f_{LV}\right)$$

where σ_{LV} is a user-defined launch vehicle margin, zero for this presentation

Inner-Loop Solver: Nonlinear Programming (NLP)

Minimize $f(\boldsymbol{x})$

Subject to:

$$\boldsymbol{x}_{lb} \leq \boldsymbol{x} \leq \boldsymbol{x}_{ub}$$
$$\boldsymbol{c}(\boldsymbol{x}) \leq \boldsymbol{0}$$
$$\boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{0}$$

where:

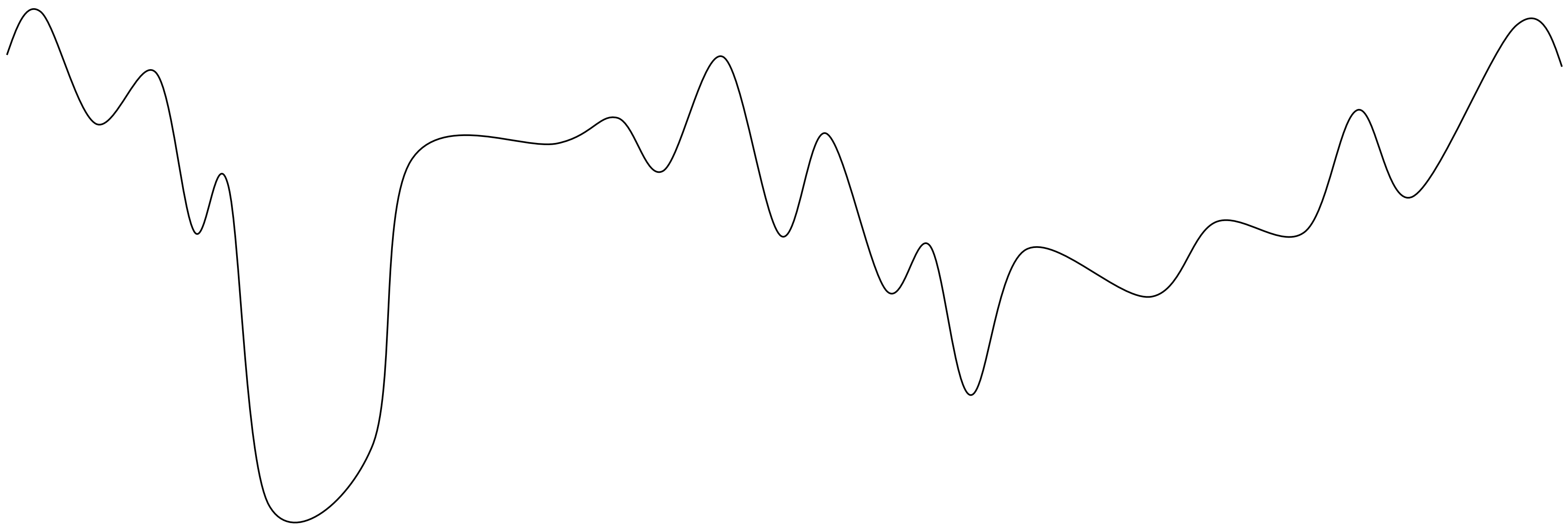
$\boldsymbol{x}_{lb}$, $\boldsymbol{x}_{ub}$ are lower and upper bounds on the decision variables

$\boldsymbol{c}(\boldsymbol{x})$ is a vector of nonlinear constraints

$\boldsymbol{A}\boldsymbol{x}$ is a vector of linear constraints

- There are several third party solvers that do this (SNOPT, IPOPT, fmincon, vf13AD)
- But all of these methods require an initial guess…

Inner-Loop Solver: Monotonic Basin Hopping (MBH)



Leary, 2000
Vasile, Minisci, and Locatelli, 2009
Yam, di Lorenzo, and Izzo, 2011
Englander (dissertation), 2013
Casioli *et al.*, 2013
Englander and Englander, 2014

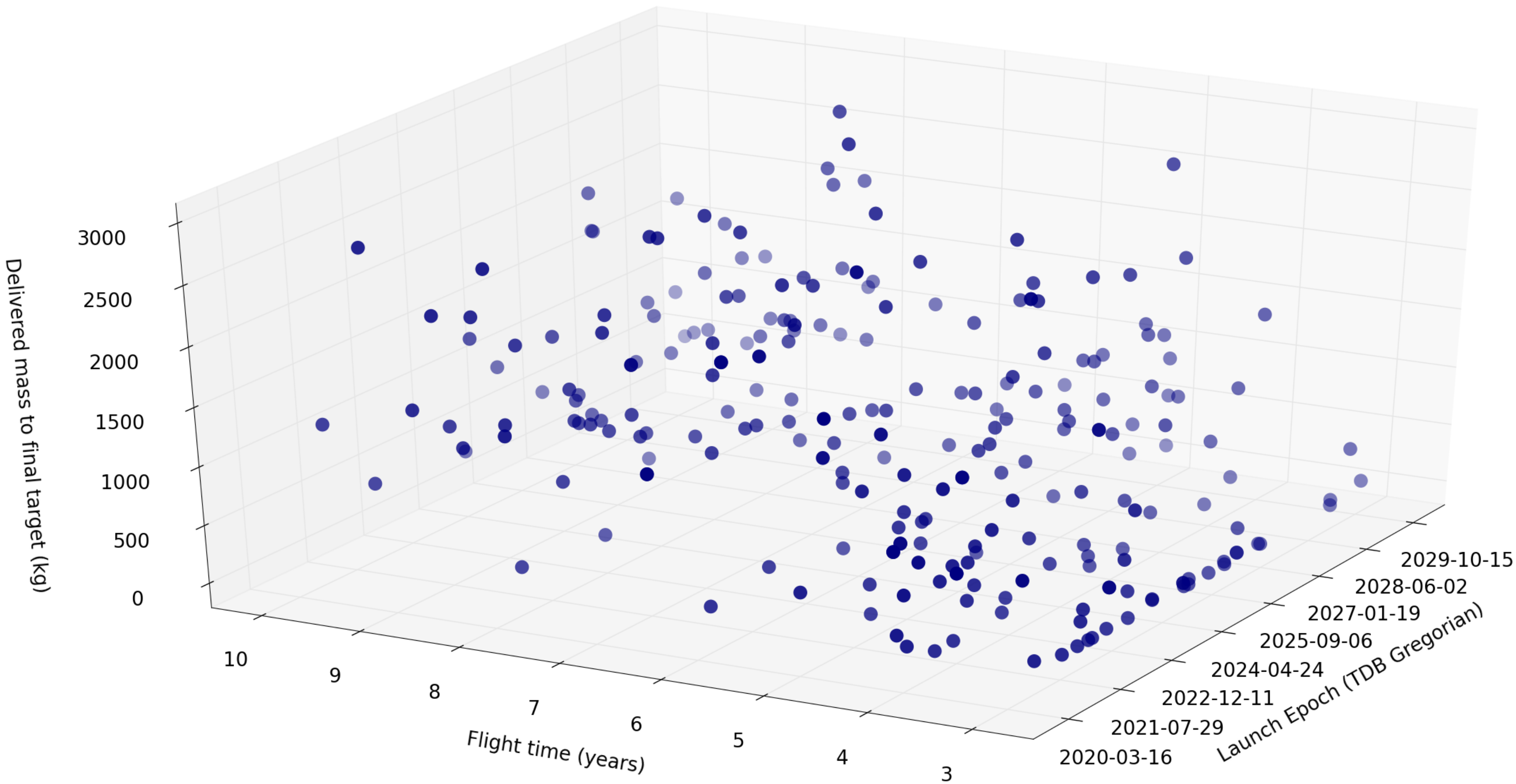
Improved from standard MBH by:

1. “Feasible point finder” aggregate penalty method
2. Non-uniform (Pareto) perturbation step
3. “Time-hop” operator (Casioli *et al.*)

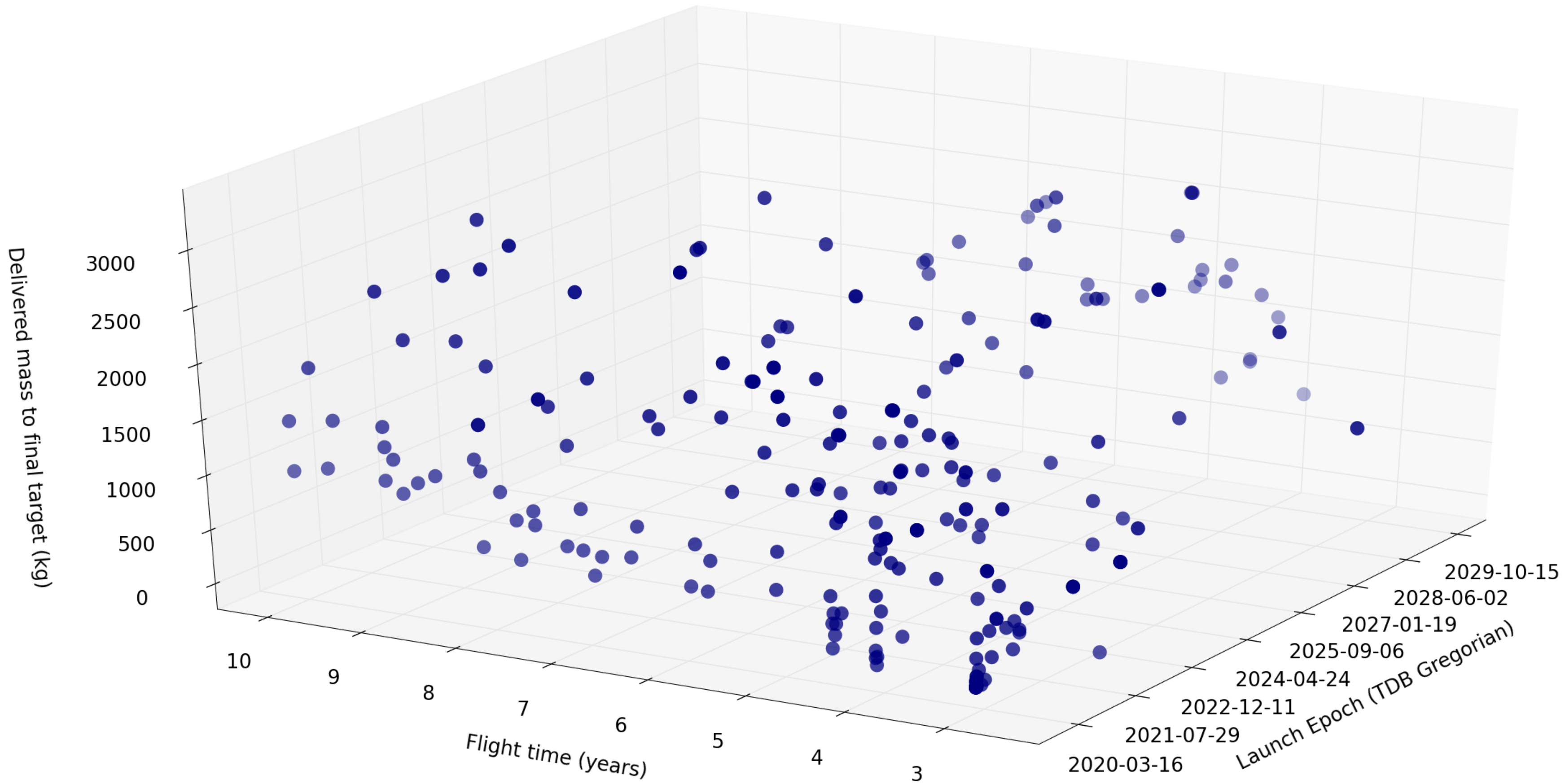
Example: A mission to Jupiter in the 2020s

Description	Value
Launch year	outer-loop chooses in [2020, 2029]
Flight time	outer-loop chooses in [3, 10] years
Launch vehicle	Atlas V 551
Spacecraft Isp	320 s
Arrival condition	insert into orbit at Jupiter
	a = 140RJ
	e = 0:91
Number of flybys allowed	up to 5
Flyby targets considered	Venus, Earth, Mars
Outer-loop objective functions	launch year flight time delivered mass
Outer-loop population size	256
Outer-loop mutation rate	0.3
Inner-loop MBH run-time	10 minutes
Inner-loop MBH Pareto α	1.3

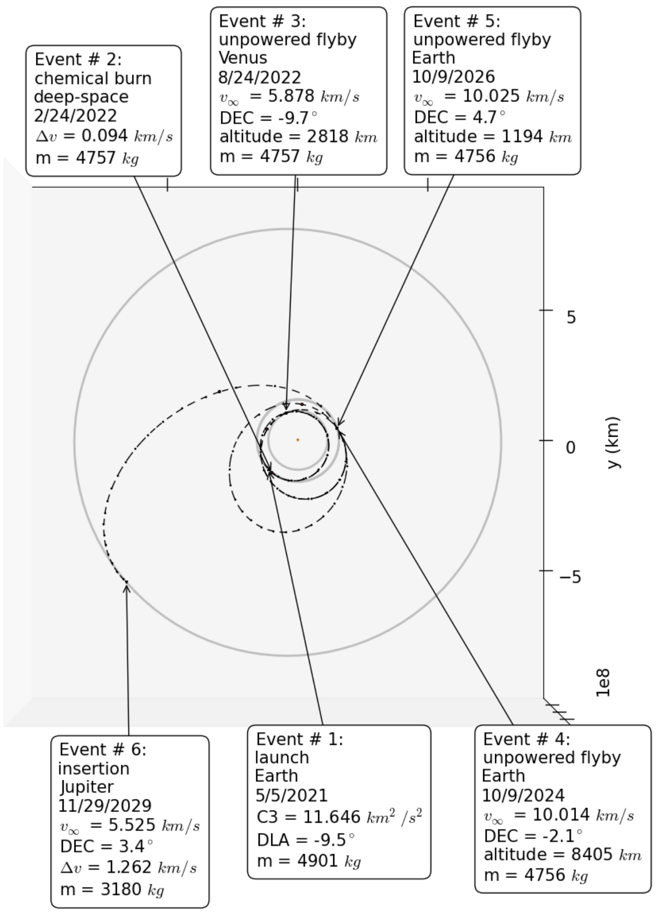
Jupiter Mission: First Generation Trade Space



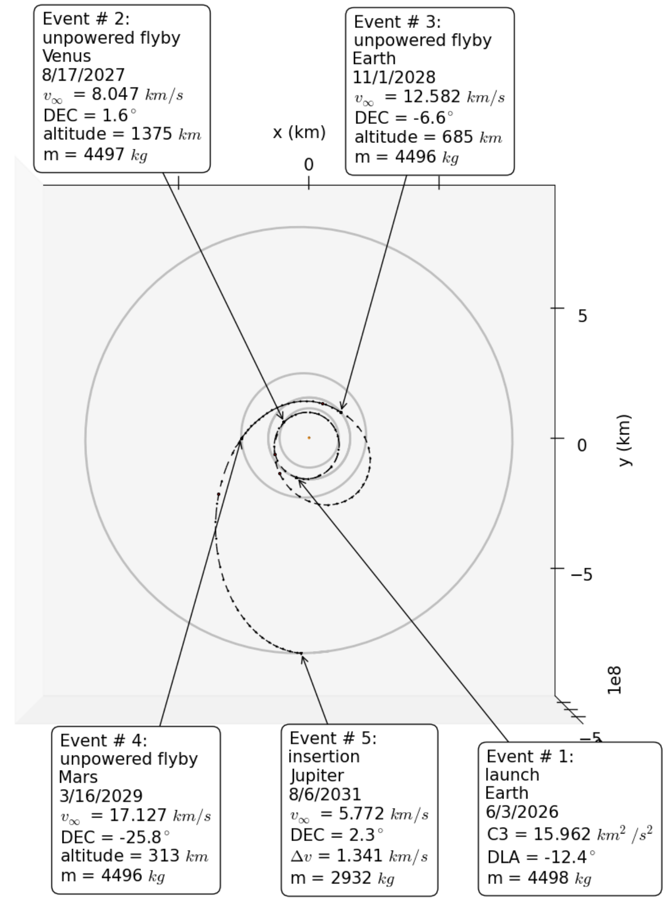
Jupiter Mission: Final Generation Trade Space



Jupiter Mission: Example Trajectories



8-year mission launching in 2021

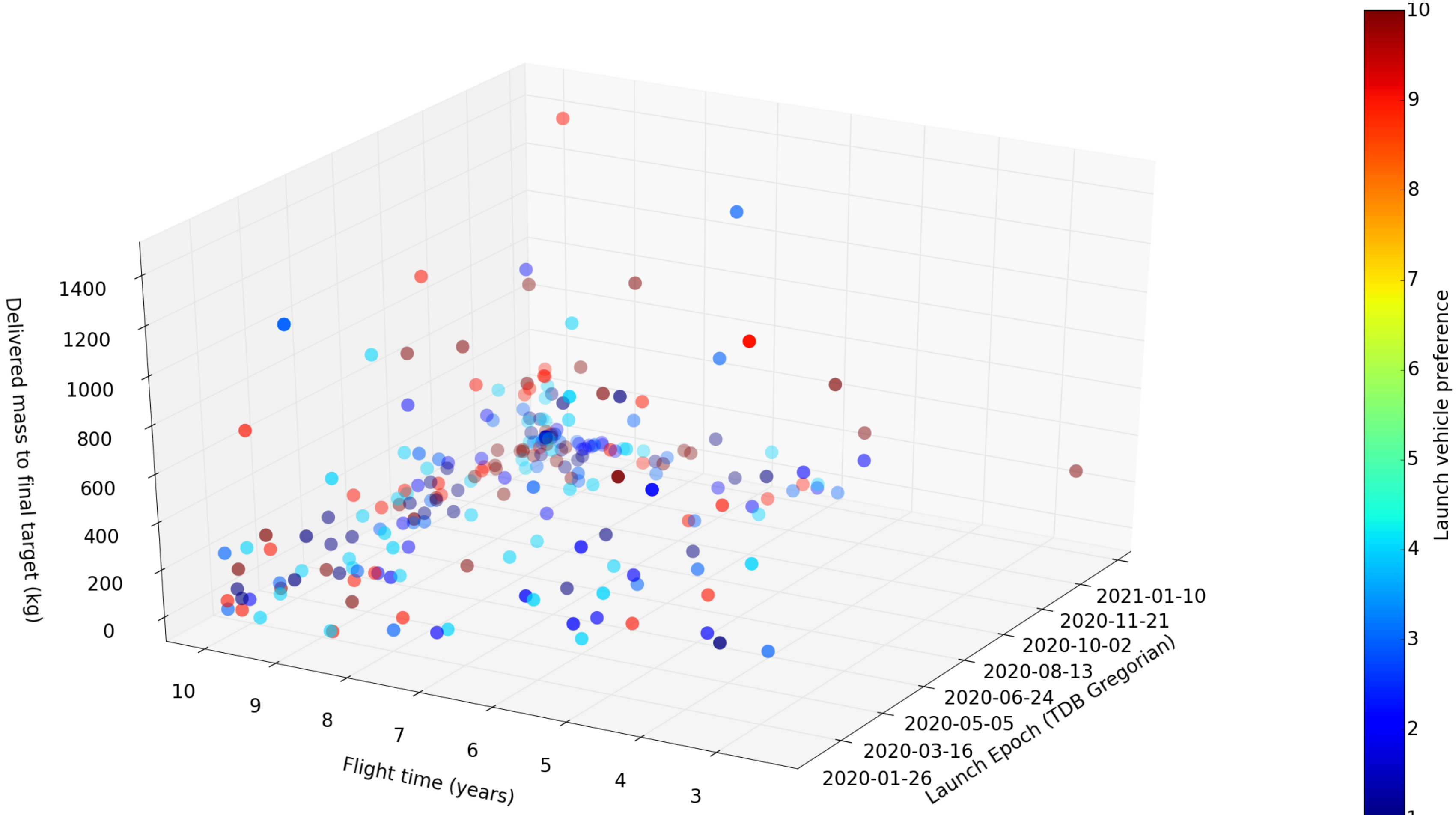


5-year mission launching in 2026

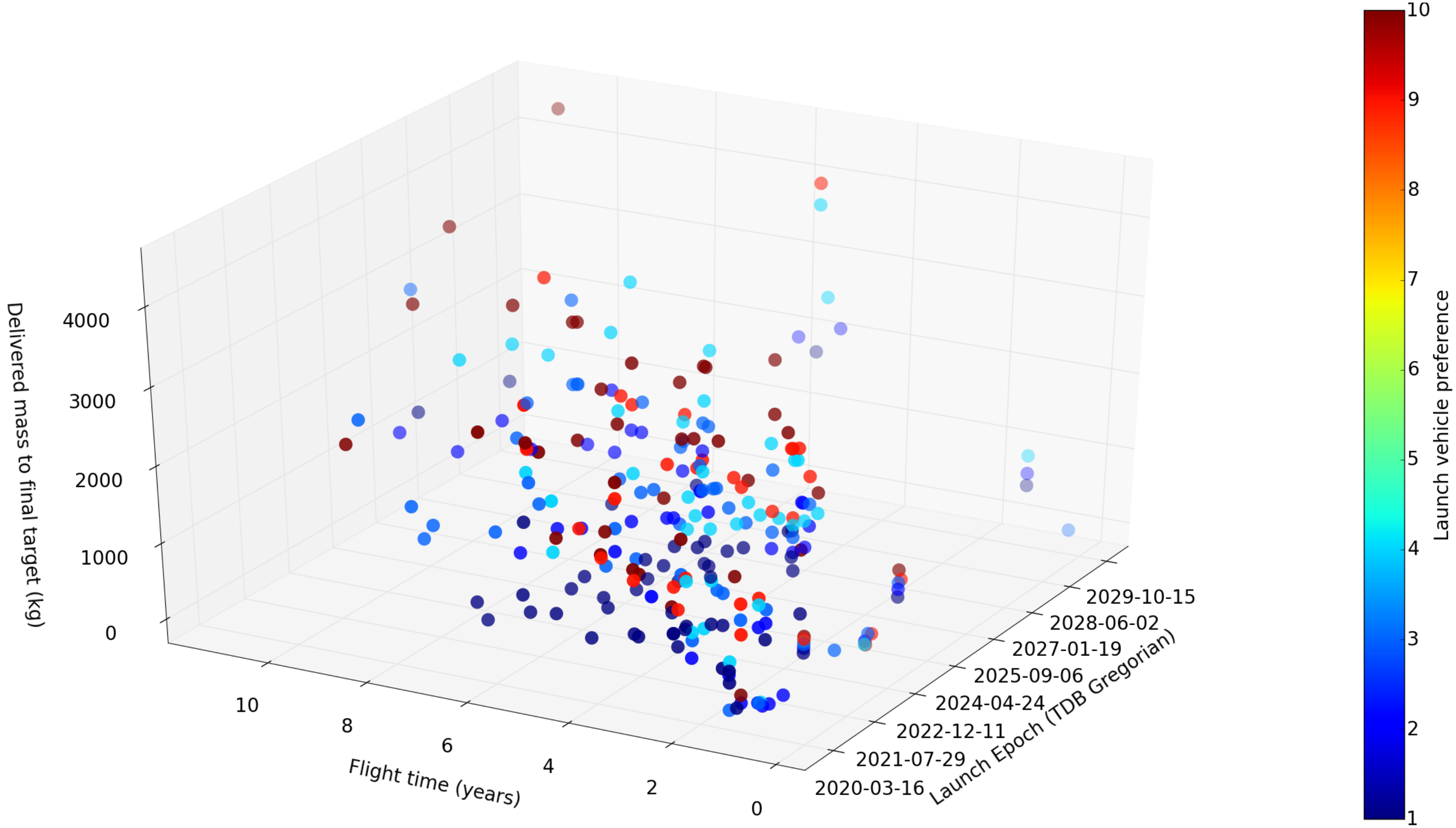
Example: Whack-a-Rock

Description	Value
Launch year	outer-loop chooses in [2020, 2029]
Flight time	outer-loop chooses in [3, 12] years
Launch vehicle	outer-loop chooses Atlas V 401, 411, 421, 431, 541, or 551
Spacecraft Isp	320 s
Penetrator mass	20 kg
Arrival conditions	
(first Journey)	intercept with v_∞ in [5.0, 10.0] km/s, $\theta_{illumination} \leq 70^\circ$
(second Journey)	rendezvous
Number of flybys allowed	2 in each Journey
Flyby targets considered	Venus, Earth, Mars
Outer-loop objective functions	launch year flight time delivered mass launch vehicle choice
Outer-loop population size	256
Outer-loop mutation rate	0.3
Inner-loop MBH run-time	10 minutes
Inner-loop MBH Pareto α	1.3

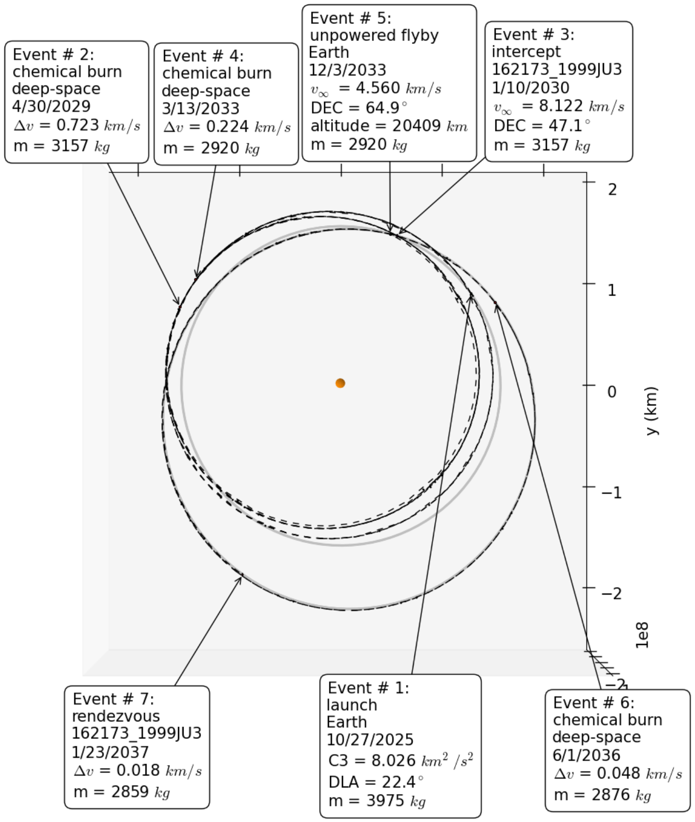
Whack-a-Rock:
First Generation Trade Space



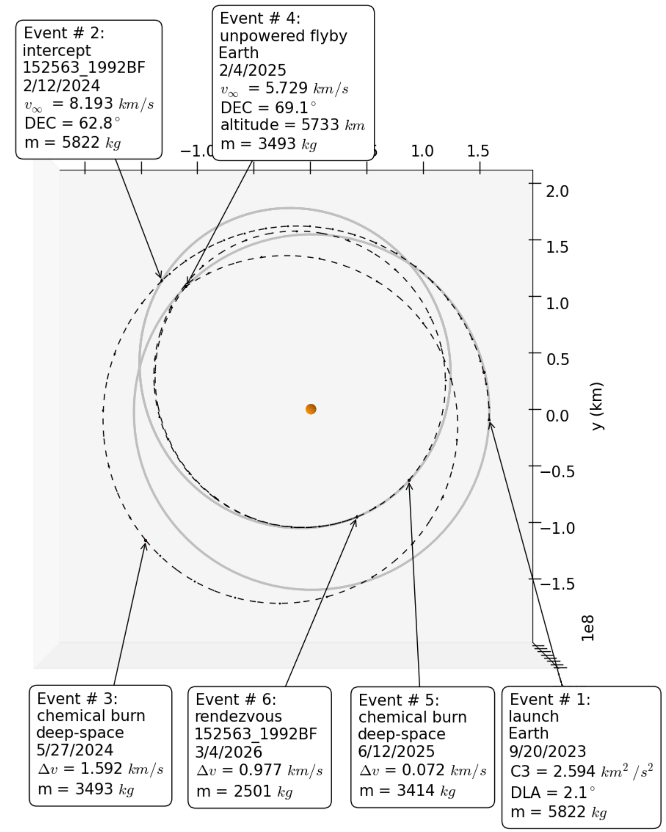
Whack-a-Rock:
Final Generation Trade Space



Whack-a-Rock: Example Trajectories



Atlas V 421, 11.25 year flight time



Atlas V 551, 2.45 year flight time

Conclusions

- The chemical interplanetary mission design problem may be posed as a multi-objective hybrid optimal control problem
- The combination of a multi-objective discrete NSGA-II outer-loop with a MBH+NLP inner-loop is a very powerful way to explore a mission trade space in an efficient, automated manner
- The algorithm described here is a valuable force-multiplier for interplanetary trajectory design
  - We can now study multiple mission design cases simultaneously, limited only by available computing power
  - Mission design engineers can now spend more time with the customer and with spacecraft hardware engineers so that we can fully understand the scientific and engineering context of our work
  - Good mission ideas are much less likely to be rejected due to lack of time to work on mission design, and bad ideas are much more likely to be rejected before they consume too many resources
- Skilled analysts are expensive. With a multi-objective HOCP automaton, analysts can focus on understanding the customer's needs and the spacecraft's capabilities and also detailed design work, leaving repetitive tasks to the computer

Thank you to our backers:

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Thank You

EMTG is available open-source at

https://sourceforge.net/projects/emtg/